A nested modeling study of elevation-dependent climate change signals in California induced by increased atmospheric CO_2

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Abstract. Dynamically downscaled climate change signals due to increased atmospheric CO_2 are investigated for three California basins. The downscaled signals show strong elevation dependence, mainly due to elevated freezing levels in the increased CO_2 climate. Below 2.5 km, rainfall increases by over 150% while snowfall decreases by 20-40% in the winter. Above 2.5 km, rainfall and snowfall both increase in the winter, as the freezing levels appear mostly below this level. Winter snowmelt increases in all elevations due to warmer temperatures in the increased CO_2 climate. Reduced snowfall and enhanced snowmelt during the winter decreases snowmelt-driven spring runoff below the 2.5 km level, where the peak snowmelt occurs one month earlier in the increased CO_2 climate. Above 2.5km, increased winter snowfall maintains snowmelt-driven runoff through most of the warm season. The altered hydrologic characteristics in the increased CO_2 climate affect the diurnal temperature variation mainly via snow-albedo-soil moisture feedback.

Introduction

Effects of the global climate change induced by an increase of atmospheric CO_2 on the hydrologic cycle in mountain watersheds are important concerns [*IPCC*, 1995]. Mountainous areas of California, where most of water supply for the region originates, exhibit a complex hydrologic cycle due to a large variation of terrain height [*Cayan et al.*, 1993; *Kim*, 1997]. Regional modeling and observational studies [*Giorgi et al*., 1997; *Leung and Ghan*, 1999; *Dettinger and Cayan*, 1995] suggest that the global warming signals in the hydrologic cycle strongly depend on terrain elevations.

Regional modeling studies of the climate change signals in California's mountain watersheds are rarely found. Statistical downscaling has been widely used in regional-scale climate change studies [*Wilby et al.*, 1998], but it is limited by a lack of physical consistency among the downscaled variables. A regional climate model (RCM) preserves physical consistency among the downscaled variables, as well as between the GCM data and the downscaled data, better than statistical downscaling [*Kim et al*., 2000]. This is important for investigating the impacts of global climate change in mountainous regions.

This study examines the climate change signals in mountain basins in California due to an increase of the atmospheric CO_2 for the 10-yr period from 2040-2049 by nesting a RCM within climate scenarios from the 2nd-generation coupled atmosphere-ocean climate model of the Hadley Center for Climate Prediction and Research (HadCM2). The climate change signals are defined as the difference between the results from the transient simulation and the control simulation. The transient and control simulations are described below.

Experimental Design

The HadCM2 simulations represent the global climate under different CO_2 concentrations at a resolution of 3.75^o longitude x 2.5^o latitude. The control and transient runs assume that the effective greenhouse gas level remains the same as the late 20th century, and increases by 1%/year starting from the year 1990, respectively. Aerosol effects are not included in the HadCM2 simulations. For details of the HadCM2 runs, see *Mitchell et al*. [1995] and *Johns et al*. [1997]. The RCM is Mesoscale Atmospheric Simulation (MAS) [*Soong and Kim*, 1996], interactively coupled with Soil-Plant-Snow (SPS) [*Mahrt and Pan*, 1984; *Kim and E*k, 1995]. MAS computes convective and grid-scale precipitation using Simplified Arakawa Schubert scheme [*Hong and Pan*, 1989] and a bulk cloud microphysics scheme [*Cho et al*. 1989], respectively. SPS computes the snow budget for a single snow layer from precipitation and snowmelt. Snowmelt is computed by solving a nonlinear form of the surface energy balance equation. The RCM domain covers the western United States at a 36x36km^2 resolution, with 18 atmospheric and 2 soil layers [*Kim et al.*, 2000].

Lateral boundary conditions and the sea-surface temperature for the RCM simulations are updated from the HadCM2 data at 12-hr intervals. The CO_2 concentrations in the RCM runs are fixed at 340ppmv and 540ppmv in the control and transient runs, respectively. Additionally, one regional climate hindcast is performed by driving the RCM with NCEP-NCAR reanalysis for the 8-yr period from 1988 to 1995. The experimental design for the hindcast is the same as the HadCM2-driven runs except the large-scale forcing.

The simulated precipitation in the hindcast agrees reasonably with that from rain gauges [*National Climate Data Center*, 1995] in California, for both above and below the 1.5 km level, over the 8-yr period. The hindcast overestimates (underestimates) precipitation above (below) 1.5km by 30% (17%). But the error does not appear to be systematic in both elevation ranges. Most of the error in the high elevation region comes from overestimating precipitation in two months, January and March of 1994. The correlation coefficients between the simulated and observed monthly precipitation ranges from 0.90 (above 1.5km) to 0.92 (below 1.5km).

An examination of the downscaled signals in 19 Sierra-Nevada basins show that the effects of CO_2-induced warming on hydrologic cycles exhibit similar dependence on terrain elevations in all 19 basins. Among the 19 basins investigated, three basins that are representative of low elevation (below 1.5km: Lower Feather River), mid elevation (between 1.5km and 2.5km: Upper Feather River), and high elevation (above 2.5km: Upper Kings River) regions are selected for presentation below.

Surface temperature signal

The downscaled low-level (10m above the ground surface) temperature signal (Figure 1) suggests that snow-albedo-soil moisture feedback strongly affects the diurnal variation of the low-level temperature. The projected increase of the low-level temperature ranges from 1K to 5K in all three basins with a large interseasonal variation. In the cold season, October-March, the daily minimum temperature (T_{min}) signal (solid line) exceeds the daily maximum temperature (T_{max}) signal (dashed line), while T_{min} and T_{ma} both increase by similar amounts from July to September. The temperature signal in May and June shows a large difference across the 2.5km level. Below 2.5km (Figure 1a,b), T_{min} increases more than T_{max}, while T_{min} and T_{max} both increase similarly above the level (Figure 1c). This spring temperature signal is due to the differences in snow depletion across the 2.5km level. Below 2.5km, most snowcover depletes in April (May) in the transient (control) run. Hence, albedo and soil moisture content (SMC) in May and June are smaller in the transient run than in the control run (not shown). Reduced albedo increases the absorbed insolation, and reduced SMC decreases evaporation and soil heat flux at the land surface. Both effects are favorable for higher daytime low-level temperature. Above 2.5km (Figure 1c), T_{max} signal slightly exceeds T_{min} signal during August and September. In this elevation range, albedo and SMC in the transient run become smaller than those in the control run during these two months as snowcover lasts until late summer.

Precipitation signal

The downscaled precipitation signal shows an increase of precipitation in all elevations, most noticeably from November to February, in response to increased moisture flux from the Pacific Ocean. Annual precipitation increase ranges from 4mm/dy in the low- and mid elevation basins to 6mm/dy in the high elevation basin. This increase corresponds to 67% (low- and mid elevation basins) and 85% (high elevation basin) of the amount in the control simulation.

Further investigations of the rainfall and snowfall changes (Figure 2) suggest that the projected warming has complex effects on the hydrologic cycle in California basins. Rainfall increases substantially from November to April in response to increased moisture flux. Snowfall decreases below 2.5km (Figure 2a-b), as the freezing level migrates to higher altitudes in the transient run. This shift is most dramatic in the mid elevation basins (Figure 2b), where the dominant form of precipitation changes from snow to rain. In the high elevation basin (Figure 2c), the effects of elevated freezing levels are small as the freezing levels appear mostly below 2.5km despite the warming. Hence, snowfall increases about 2.5km in response to increased moisture flux.

Snowmelt and runoff signal

In response to the warming of the low troposphere, snowmelt increases in all elevations from December to March (Figure 3). Below 2.5km, spring snowmelt is reduced in the transient run (Figure 3a-b), as reduced (enhanced) winter snowfall (snowmelt) results in reduced snow accumulation at the beginning of the spring. In the two lower elevation basins, the peak snowmelt timing shifts by one month, from May to April. *Dettinger and Cayan* [1995] suggest that this shift in the peak snowmelt timing is already in progress in California basins. Unlike the lower elevation basins, snowmelt timing does not shift in the high elevation basin (Figure 3c).

The changes in precipitation and snowmelt strongly affect runoff (Figure 4). Below 2.5km, runoff increases from November to March due to increased cold-season rainfall and snowmelt. As snow depletes early due to reduced (enhanced) winter snowfall (snowmelt), the snowmelt-driven runoff peak in May, which is clear in the control run, disappears in the transient run (Figure 4a,b). In high elevations (Figure 4c), runoff increases throughout the year due to increased rainfall and snowmelt during the cold season, and increased snowmelt during the warm season. The snowmelt-driven spring runoff peak appears only in the high elevation basin under the increased CO_2 climate.

Summary and discussions

Effects of increased atmospheric CO_2 on the hydrologic cycle from a RCM nested within two global climate scenarios from HadCM2 show strong elevation dependence in California basins. The detailed spatial structures due to complex terrain of the region in the downscaled climate change signal, which are not available from the GCM, enhance the value of GCM-projections for assessing the impacts climate variations on regional hydrologic cycle.

The downscaled signals suggest that precipitation would increase in all elevation ranges in California, especially during the cold season, due to increased moisture flux from the Pacific Ocean. Below 2.5km, winter rainfall increases substantially, while snowfall decreases as the freezing level migrates to higher altitudes due to the projected CO_2-induced warming. Above 2.5km, both rainfall and snowfall increase during the winter, as the freezing level appears mostly below the level. Snow accumulation at the end of the winter decreases below the 2.5km level while it increases above it due to the changes in precipitation characteristics and snowmelt associated with the projected warming. The snowmelt-driven spring runoff peak disappears in the low- and mid elevation basins due to early snowmelt and reduced snowfall. Snowmelt timing does not change in a high elevation basin. The downscaled signals imply large impacts on water resources in California. A large increase of winter runoff requires a measure to prevent flood damage. Reduced snowmelt-driven spring runoff in most mountain basins causes shortage of water resources during the warm season.

Downscaled climate change signals presented in this study are consistent with the signals from the GCM, with more detailed spatial structure. The main source of uncertainties in the downscaled signal is GCM-generated global-scale signals, as projected climate change signals vary widely among the GCMs [*IPCC*, 1995]. An ensemble projection based on multiple GCMs and RCMs may be useful to reduce uncertainties in projecting regional climate change signals.

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Figure Captions

Figure 1: The downscaled climate change signal (K) in the daily minimum (solid line) and maximum (dashed line) temperatures for each month in the three Sierra-Nevada basins. The number in the parenthesis following the basin name is the average terrain height (m) of the basin.

Figure 2: The monthly-mean rainfall and snowfall (mm/day) in the three basins from the control (bar) and the transient (lines) runs. The bars and dashed line at the bottom of the frame indicate rainfall. The bars and solid line at the top of the frame, with an upside-down scale, indicate snowfall.

Figure 3: The monthly-mean snowmelt in the control (bar) and transient (line) runs.

Figure 4: Similar to Figure 3, but the monthly-mean runoff.